3. RADIATION MEASUREMENTS

3.1 OVERVIEW

Since about 1950, the Environmental Measurements Laboratory has carried out major research programs directed at the study of ionizing radiation and natural and man-made radionuclides in the working and in the public environment. Among these studies have been: (1) the long-term investigation of the atmospheric distribution and ground deposition of radionuclides from global fallout generated by nuclear weapons tests; (2) the evaluation of the radiation exposure of human populations from these nuclides as well as those deposited locally by the Nevada weapons tests, those released from nuclear facilities (including the reactor accidents at Three Mile Island and Chernobyl), and those normally present from natural sources; and (3) the determination of radiation worker exposures at particle accelerators, nuclear reactors, and other nuclear facilities. An important component of these studies has been the development and improvement of techniques for low-level radiation measurement and data interpretation. In the following sections, five highly generic measurement systems are described that have been developed and/or refined at EML, and that have found wide application in environmental radiation studies. In each case, an essential part of the system is the methodology associated with detector calibration, measurement procedure(s), and data analysis and interpretation. The indicated references provide additional details and examples of applications for the interested reader.

3.2   IONIZATION CHAMBERS

Contact Person: Kevin M. Miller

3.2.1   SCOPE

This section describes the design, analysis procedures, calibration, and use of pressurized ionization chambers (PIC). These instrument systems are used at EML in the assessment of the penetrating component (gamma plus cosmic-ray secondaries) of the environ-mental radiation field. Accurate and highly precise measurements of the total exposure rate (or dose rate in air) are made of such sources as:

1.   cosmic-ray secondary radiation (high energy muons, photons, and electrons) in the lower atmosphere;

2.   natural background radiation from primordial radionuclides (and progeny) in the soil and air;

3.   anthropogenic isotopes associated with

   a. direct radiation from nuclear facilities,
   b. gaseous effluents from nuclear operations,
   c. fallout deposition,
   d. residual radioactivity at sites undergoing clean-up.

3.2.2   PIC SYSTEM DESIGN

3.2.2.1
ION CHAMBER

The chamber selected as our standard consists of a 25-cm diameter stainless-steel sphere with a wall thickness of 2.37 g cm^2 filled to a pressure of 2.5 MPa (25 atmospheres) with ultrapure Ar gas. The collecting electrode is a 5-cm diameter hollow sphere at the center of the chamber supported by a 0.6-cm diameter rod, which in turn is connected to the chamber shell at the center of a triaxial metal-ceramic seal. The middle conductor of this seal serves as a guard ring and is kept at true circuit ground. A 300-V battery is used to provide bias to the

outer shell. This voltage along with the large center electrode results in complete charge collection in fields of up to 10 μGy h^{-1}.

Smaller versions of this chamber are also routinely used. They consist of an 18-cm diameter sphere with the same or slightly thicker wall and filling pressures of up to 3.7 MPa. The collecting electrode for these chambers measures 1.9-cm in diameter. Complete charge collection has been observed at 400 μGy h^{-1} with a bias of 300 V.

A complete description of experimental and theoretical investigations involving various PIC designs can be found in De Campo et al. (1972). Known commercial suppliers of these PICs are GE Reuter-Stokes (Twinsburg, Ohio 44087) and LND, Inc. (Oceanside, New York 11572).

3.2.2.2
ELECTROMETER

The ion current from the PIC is measured with a temperature compensated electrometer consisting of a MOSFET (metal oxide semiconductor field effect transistor) and an operational amplifier using 100% negative feedback from the amplifier output to the MOSFET input (Negro et al., 1974). Stable voltage regulators, external to the electrometer, are used to provide power. The electrometer itself is small and light enough to attach directly to the triaxial connector on the PIC and suspend freely without additional support. This arrangement minimizes mechanical stress on the seal insulators and any resultant piezo-electric currents. The response to radiation is about 3 fA per nGy h^{-1} for the large 2.5 MPa chambers and about half that for the 3.7 MPa small chambers. A glass encapsulated tera-ohm carbon resistor used in the feedback loop of the electrometer determines the output sensitivity, generally about 3 mV per nGy h^{-1}, and time response, generally on the order of a few seconds. The electrometer saturates at somewhat over 5 V, which translates to about 1700 nGy h^{-1}.

3.2.2.3
READOUT SYSTEMS

Direct observation of the electrometer output voltage is made with a standard voltmeter. To obtain precise measurements, signal integration is performed by one of two methods listed below.

A. Survey mode.

For real-time results, a voltage-to-frequency converter with scaler and calibrated digital readout is used to provide readings with selectable integration times of 4, 40, or 400 sec. This readout system is generally used with the 18-cm diameter chambers in the form of a two-unit package called a SPICER (small pressurized ionization chamber for environmental radiation; Latner et al., 1983). The system is battery powered and can be either held in hand or tripod mounted. Figure 3.1 shows the system in this latter mode of operation.

B. Monitor mode.

The second read-out method is designed for continuous remote monitoring. It consists of an analog to digital converter, timing and control circuitry, and a magnetic tape cassette recorder (Memodyne, Model 201) housed in a weather proof aluminum box (Cassidy et al., 1974). The ion chamber and electrometer are packaged in a similar box which sits atop the recorder box during operation in the field as shown in Figure 3.2. The standard system records the digitized electrometer output voltage every 10 sec, and is capable of storing up to 17 days of data on a single cassette. Some units have been modified to allow the option of recording every 10, 20 or 40 sec. An alkaline cell battery pack provides power for 8 weeks of operation.

3.2.3 DATA ANALYSIS

The magnetic tape cassette is read out with a Memodyne 3122 ABV reader interfaced to a Hewlett-Packard 9826 computer using a specially developed analysis program (Gogolak, 1982). The analysis procedure is as follows:

1. A 6 h record of the 10-sec data is read into the computer and displayed on a screen.

2. The data is averaged over 5-min intervals, corrected for the zero reading of the electrometer and converted to exposure rate via a chamber specific calibration factor.

3. A printout of the 5-min averages as well as the average over each hour is made. The standard deviation (SD) of the 5-min data for each hour is also computed and printed.

4. Subsequent 6-h records are analyzed and at the end of the tape a summary plot of the hourly data is made. Bad data sections are then edited and a final printout and plot of the corrected hourly average and SD data is obtainedThe hourly average maximum and minimum and daily average are also printed for each day along with the average over the entire period.

5. Permanent storage of the corrected 5-min data is made on a diskette.

6. If desired, the data can be analyzed for any dose due to the passage of a plume (Gogolak and Miller, 1974). The analysis routine examines the SD of the 5-min data in each hour and if it is sufficiently high (> 1.7 nGy·h^{-1}) it is assumed that a fluctuating plume component was present. A search is then made on each side of the plume hour for the nearest three background hours indicated by a standard deviation that is sufficiently low (< 1 nGy·h^{-1}). The average background is computed from these 6 h and subtracted from the total dose in the plume hour to yield the net plume dose.

3.2.4 **CALIBRATION**

Calibration of the PIC is performed using a National Institute of Standards and Technology (NIST) certified sealed 37 MBq ^{226}Ra source and a shadow shield technique (De Campo et al., 1972). The shadow shield method is necessary because it removes the contribution of the room scatter component which we have found to be on the order of 30% of that from the primary beam. At the same time, it also corrects for any other constant factors included in the PIC output such as room background, electrometer zero offset, and α and stress currents. The calibration procedure is as follows:

1. The source is placed in a low mass holder at a height of about 1 m above the floor and at a distance of 4, 5, or 6 m to the PIC (geometric center), which is at the same height on a low mass stand.

2. A 30-cm thick lead shield with a cross section measuring 10-x-10 cm is interposed on a low mass stand so as to intercept all primary rays from the source to all parts of the PIC through the full thickness of the shield. Alignment is checked with a string with a dummy source in place. Slight overshielding (a larger shadow) on the order of 1-2 cm is used as this results in a negligible error as opposed to undershielding which could produce a significant error. The use of a shield with a cross section that is roughly half that of the PIC is recommended because the shadow size cast will require the shield to be placed near the midpoint between the source and the PIC thus minimizing the production and interception of lead fluorescent X-rays and also allowing a proper alignment which is not too critical to shield placement.

3. The source is placed in its holder and the output signal of the PIC is averaged over a 10- to 30-min time period.

4. The lead shield is removed (leaving its stand in place so as to change the scattering conditions as little as possible), and the PIC output signal is averaged again over a 10- to 30-min period.

5. The difference between the average signals (reading with shield not in place minus reading with shield in place) is divided by the exposure rate delivered by the source at that distance to yield the Ra primary beam calibration factor. This calibration factor must be adjusted by a small amount for the energy spectrum that will be encountered for a particular radiation field. For our standard 25 cm-2.5 MPa chamber, this correction yields a 3% higher sensitivity for a normal background radiation field, while for the 18 cm-3.7 MPa chamber it is 1% higher.

6. Background readings are taken in the calibration room and in a whole body counter in both the negative and positive high voltage modes of operation to verify that the system does not have stress currents present and that there is no high internal background.

3.2.5 **INFERRING EXPOSURE (DOSE) RATE**

The total PIC current can be expressed as

$$R \ = \ k_c I_c \% k_t I_t \% R'$$

where

k_c = the calibration factor for cosmic radiation
I_c = the cosmic radiation exposure rate
k_t = the calibration factor for terrestrial radiation
I_t = the terrestrial radiation exposure rate
R' = the α particle current from contamination in the steel shell (~2 fA for the 25-cm chamber and 1 fA for the 18-cm chamber)

For our standard chamber, the values of k_c and k_t are only 1% different so that for most applications the total exposure rate ($I_c + I_t$) is inferred by simply subtracting the α current from the total current and dividing by the factor corresponding to the dominant component of the radiation field. (In a strict sense, the quantity "exposure rate" is only applied to γ rays of certain energies. However, for environmental radiation fields it is convenient to extend the meaning to include the exposure rate equivalent of ionization in free air due to cosmic rays.) For expressing the exposure rate in SI units, the appropriate quantity would be

C kg^{-1} s^{-1} or A kg^{-1}. Since this is a rather unfamiliar unit, we prefer to convert the exposure rate to dose rate in air when reporting data in SI units.

A more accurate estimate of I is derived by substituting a value for I_c in the above equation. To do this, the altitude of a measurement site is determined using a topographical map or the barometric pressure is measured. The corresponding cosmic-ray exposure rate (dose rate in air) is inferred using the data presented in Figure 3.3. It should be noted that I will vary with the 11 year solar cycle, being a few percent higher (lower) at solar minimum (maximum) (O'Brien, 1972).

Although not common with the small freely suspended MOSFET electrometer, stress currents can result from mechanical pressure on the ionization chamber insulator. The presence of these unidirectional currents is checked by reversing the high voltage polarity on the ion chamber shell. After correcting for the electrometer zero offset, the readings should agree if no stress current is present. If the readings do differ, the true reading is just the arithmetic average of the two.

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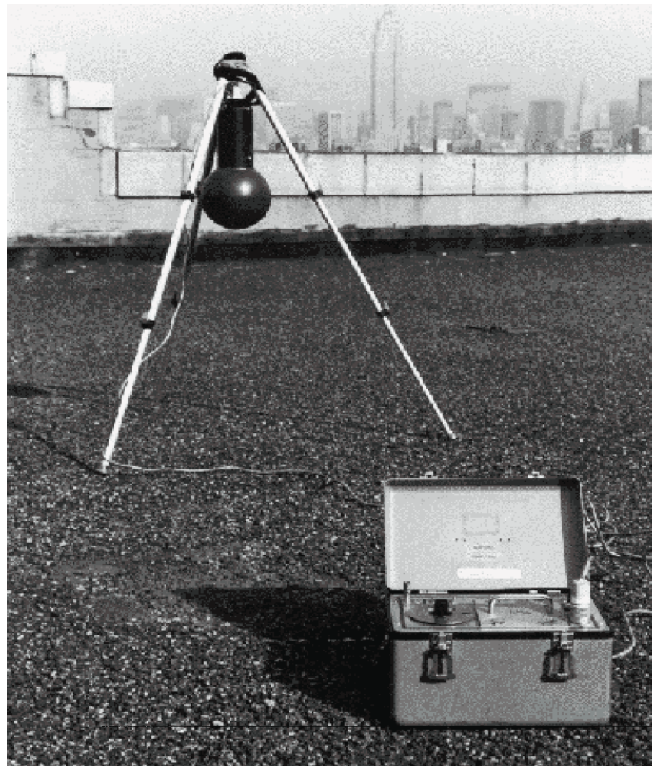USERDA CONF-720805-P1, Vol. 1, pp. 15-54 (1972)

Figure 3.1. SPICER system set up for field measurements showing a tripod mounted ion chamber with an electrometer unit connected via cable to the digital readout box.
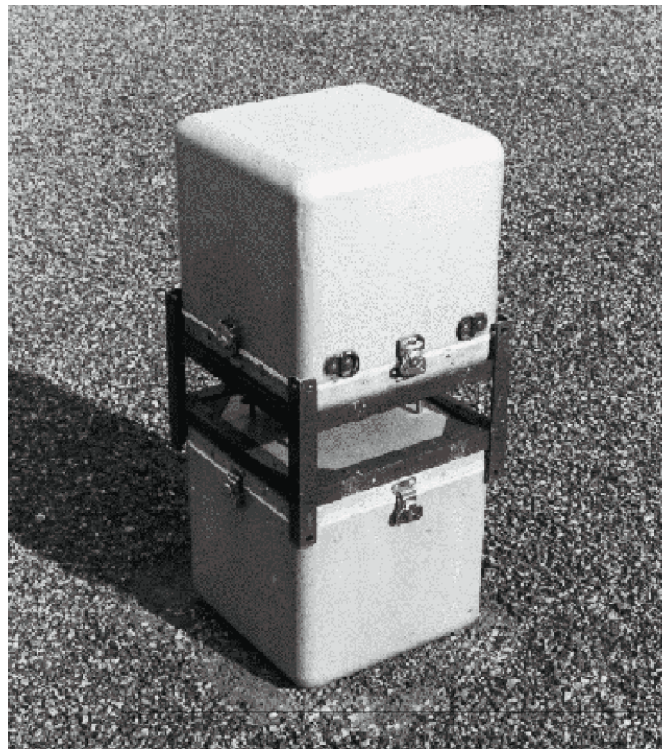

Figure 3.2   PIC system for field monitoring. The chamber and electrometer are housed in the top box, and the digital recorder unit is contained in the bottom box.
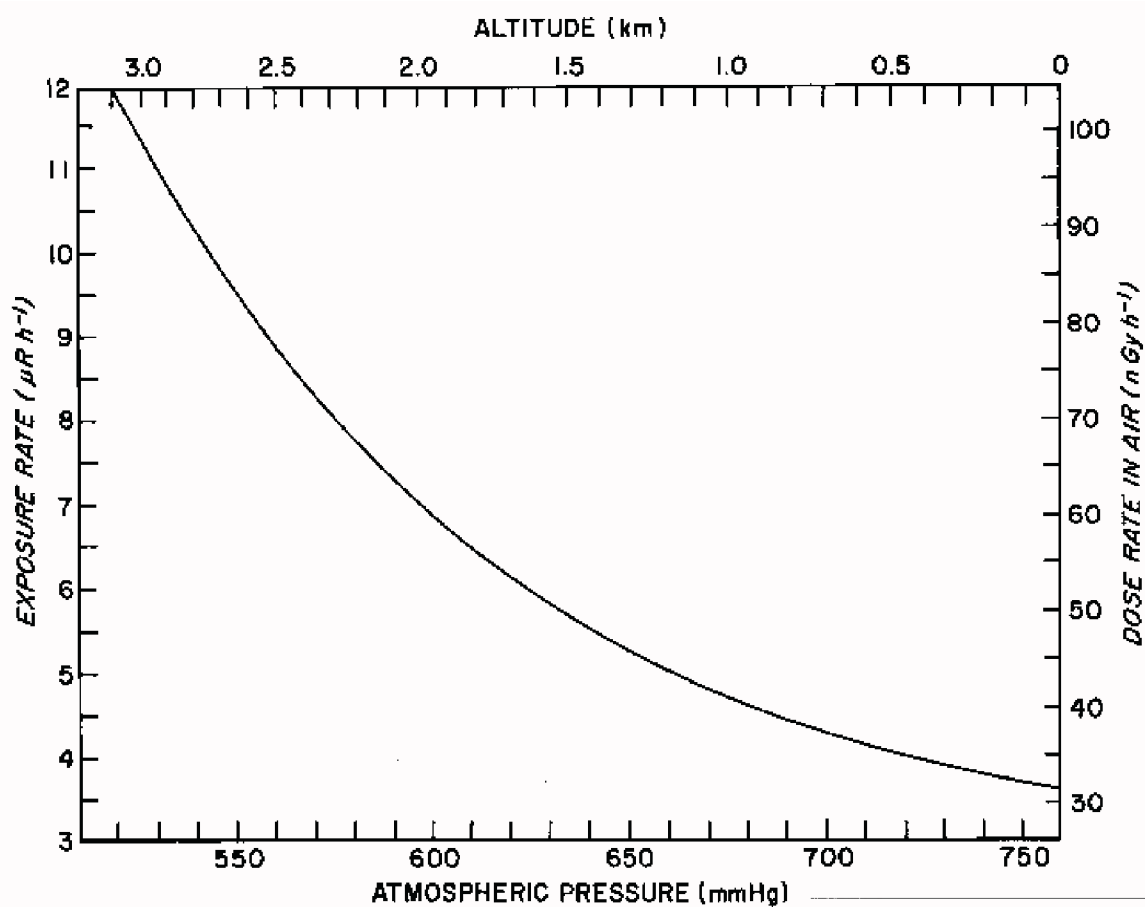
Figure 3.3   Cosmic-ray exposure rate equivalent and dose rate in air as a function of atmospheric pressure and altitude for mid-latitude.

3.3 FIELD GAMMA-RAY SPECTROMETRY

Contact Person: Kevin M. Miller

3.3.1 SCOPE

This section describes the instrumentation, setup, calibration and analysis for EML's field (*in situ*) γ-ray spectrometry using high resolution Ge detectors. The specific application to inventory measurements is described, as well as a spectral stripping routine for total exposure rate measurements. Methods for low resolution NaI detectors are also given.

Field spectrometry is used at EML for the rapid identification of radionuclides in the environment. When the source geometry is taken into account, the concentrations or inventories (activity per unit area) of these radionuclides in the soil can be inferred along with the contribution to the above ground exposure rate. Applications have included:

1. the measurement of natural background and weapons test fallout emitters (Lowder et al., 1964a, b; Beck, 1966; Beck et al., 1964);

2. indoor radiation studies (Miller and Beck, 1984);

3. analysis of power reactor plumes (Gogolak, 1984);

4. the determination of aged fallout levels in terrain with mixed ground cover (Miller and Helfer, 1985).

5. site characterization for environmental restoration (Miller et al., 1994).

3.3.2 INSTRUMENTATION

Although field spectrometry can be performed with a NaI scintillator, the detector of choice at EML for most applications is a high resolution hyperpure germanium coaxial crystal. This type of detector can sustain warmup when not in use, which is a convenient feature during extended field trips.

Ease of handling is best accomplished with a detector mounted in a cryostat that is small (hand-held) and which has an all-attitude capability. Ideally, the detector assembly should be mounted on a tripod with the crystal endcap facing down toward the ground and the dewar

above. This orientation maximizes the flux that will be intercepted and registered by the detector. However, a standard 17- or 30-L dewar with an upward facing endcap can still be used without a large loss in efficiency, since most of the flux is incident at the sidewall of the detector, with the dewar blocking out only a few percent of the ground area that is effectively being measured. In either the downward or upward facing geometries, the axis of rotation for the cylindrical crystal is perpendicular to the ground plane. As such, the detector can be assumed to have a symmetrical azimuthal response. A "goose neck" cryostat, where the crystal axis is parallel to the ground plane, should be avoided since this introduces asymmetry and would require making complicated angular corrections.

Counting times in the field can be reduced by using large volume detectors, however, the crystal length/diameter ratio is an important consideration as well. The standard method of measuring the efficiency for a Ge detector is performed with ^{60}Co source at 25 cm normal to the detector face. As mentioned above, the open field source geometry is such that most of the flux is incident from the side. Thus, for two detectors that have the same quoted efficiency, a long thin crystal will yield a higher count rate in the field as compared to a short wide one. However, length/diameter ratios close to unity would generally result in less uncertainty in measurements due to flatter angular responses.

A list of detectors that we have calibrated for field spectrometry is given in Table 3.1. Our current primary detector for field work is the 45% efficient high purity P-type Ge coaxial mounted in a portable (hand-held) cryostat. It requires a 6 h cool-down time before becoming operational, although it is normally mated to an overhead 30-L liquid nitrogen dewar with a gravity feed system when stored in the laboratory so that it is always ready for use. This type of setup also allows the detector to be placed in a shield and used for sample analysis. Once cooled down and detached from the feeder dewar, the hand-held cryostat (1.2 L) can be used for as long as 24 h before refilling is required. For studies involving low energy, a recently acquired detector measures 75% in relative efficiency and is of N-type Ge with a beryllium window. It has a 3-L dewar and can be hand-held although it is best suited for tripod mounting.

Generally, measurements are made in the field using a portable battery-powered computer-based spectroscopy system. High voltage and preamplifier power are supplied to the detector by the system. Some detectors feature low power preamplifiers which provide for extended operational time when using battery power in the field. A spectroscopy grade amplifier is also contained within the system. The complete spectrometer system can be carried and operated by one person.

3.3.3   SITE SELECTION AND INSTRUMENT SETUP

The detector is placed ~1 m above the ground with the analyzer and operator positioned a few meters away. The site chosen should be a flat, relatively even and an open area. Terrain that has obstructions such as boulders, large felled or standing trees, and any man-made structures should be avoided as these will block the γ flux from the underlying soil. Extreme ground roughness will result in anomalies since the soil surface area close to the detector is increased, while the surface contribution from large distances is reduced. For measurements of fallout radionuclides, the area must be undisturbed in that water and wind erosion as well as human activity, such as cultivating, would tend to upset the distribution of any deposited activity. Figure 3.4 shows an example of equipment placement at a typical field site.

When selecting a site for measurement, the source geometry must be taken into account. An unshielded detector, placed at 1 m above the ground, samples the photon flux from a volume of soil out to a radius on the order of 10 m and down to a depth of about 30 cm, depending upon the photon energy. Figure 3.5 shows a pictorial representation of the relative ground area contributions to the primary (uncollided) flux at a height of 1 m for a medium energy (662 keV) source with a typical exponential depth profile in the soil. This effective "field of view" varies, being somewhat larger (smaller) for higher (lower) energy sources. Also, activity that is closer to the soil surface will produce a wider field of view.   In effect, a field spectrum samples an area of several hundred square meters, thus averaging out the local inhomogeneities in the distribution of the radionuclides. The source being measured is essentially a giant soil sample and counting statistics for a given spectral absorption peak are obtained in a fraction of the time required for counting a small collected sample.

A good practice to follow is to make a series of short measurements in an area to ensure that there is approximate uniformity before collecting a longer spectrum and obtaining the desired counting statistics. When making measurements of natural background, or when the exposure rate is dominated by the man-made emitters under study, this check can be performed with an ionization chamber or a suitably sensitive survey ratemeter in that uniform exposure rate readings would imply a spatially invariant source distribution relative to the detector. If the particular radionuclides under study contribute just a small fraction to the total exposure rate, then the corresponding peak area count rates should be checked with the spectrometer to ensure uniformity.

3.3.4   CALIBRATION

A complete description of field γ-ray spectrometry can be found in Beck et al. (1972) and Miller and Shebell (1993). To summarize, the exposure rate in air above the ground is related to the absorption peak counting rate registered by the detector by

$$\frac{N_f}{I} \;=\; \frac{N_0}{\varphi}\,\frac{N_f}{N_0}\,\frac{\varphi}{I} \tag{1}$$

where

   N_o/φ is the counting rate from a particular spectrum absorption peak due to a unit primary photon flux density of energy E incident on the detector along the detector axis (normal to the detector face).

   N_f/N_o is the correction required to account for detector angular response, and

   φ/I is the primary photon flux density with an energy E at the detector resulting from the decay of a particular radionuclide per unit exposure rate at the detector from all primary and scattered photons originating from this nuclide and any others present from its radioactive decay series.

   The first two terms depend on the particular detector. φ/I values depend only on the source composition and geometry and can be used for any spectrometer calibration.

   In a like manner, the concentration or inventory of a particular nuclide is related to absorption peak counting rate by

$$\frac{N_f}{A} \;=\; \frac{N_0}{\varphi}\,\frac{N_f}{N_0}\,\frac{\varphi}{A} \tag{2}$$

where φ/A is the total photon flux density at the detector location per unit concentration or inventory of the nuclide.

   The three factors to compute N_f/I or N_f/A are discussed separately.

A. N_o/ϕ.

The response to unit flux at normal incidence is evaluated for a detector using various γ-ray point sources. A complete energy response curve from 40 keV to 3 MeV can be inferred with a set made up with the reasonably long lived isotopes ^{152}Eu, ^{241}Am, ^{137}Cs, ^{60}Co, and ^{228}Th. The measurement procedure is as follows:

1. Position the source at a distance of at least 1 m and at normal incidence to the detector face.

2. Calculate the uncollided flux density at the detector effective crystal center, which is obtained by dividing the γ emission rate by $4\pi\ r^2$. The value of r is the distance from the source to the crystal effective center. This can be taken to be the geometric center for high energy (> 1 MeV) rays and the crystal face for low energy (< 0.1 MeV) rays. For the energy range between these two values, an estimate of average penetration distance can be made based on the absorption coefficient of the crystal. The flux density is also corrected for air and source holder attenuation.

3. Collect a spectrum and determine the full absorption peak count rate.

4. Collect a spectrum without the source present and subtract out from the previously measured count rate any contribution to the peak from background emitters.

5. Divide the corrected count rate by the flux density to determine N_o/ϕ.

6. Perform this measurement at different energies with either simultaneous or separate runs.

7. Plot the values of N_o/ϕ versus energy on a log-log scale and fit the data to a smooth curve. Figure 3.6 shows N_o/ϕ as function of energy above 200 keV for the detectors listed in Table 3.1. In the energy range shown, the response can be fit to a straight line on a log-log plot to within $\pm 3\%$.

B. N_f/N_o.

The uncollided γ-ray flux for a soil half space source geometry is not limited to angles normal to the detector face. Therefore, the complete flux density response calibration must account for the fact that a cylindrical Ge crystal when oriented with the axis of symmetry perpendicular to the ground plane has a variable altitudinal (zenith-angle) response. The correction factor, N_f/N_o, is determined from point source calibrations as functions of energy and angle in the vertical plane and can be calculated from

$$\frac{N_f}{N_0} \cdot \int_0^{\frac{x}{2}} \frac{\phi(\theta)}{\phi} \frac{N(\theta)}{N_0} d\theta \qquad (3)$$

where

$\phi(\theta)/\phi$ is the fraction of the total primary flux at zenith angle θ for a given source energy and geometry, and

$N(\theta)/N$ is the response of the detector at angle θ for the same energy γ ray relative to the response at normal incidence.

  The procedure for determining the values of N_f/N_o is as follows:

1. Measure the full absorption peak count rate (minus any background contribution to the peak) using a point source at a fixed distance of at least 1 m to the crystal at 15° intervals between incident angles of 0° (normal to detector face) and 90°.

2. Plot the relative response $N(\theta)/N$ versus angle and fit the data to a smooth curve.

3. Evaluate Equation 3 numerically for at least three different source distributions in the soil (surface plane, 3 cm relaxation depth, and uniform). The angular flux distribution data can be found in Beck et al. (1972).

4. Repeat Steps 1-3 for several other energies and plot the resultant values of N_f/N_o versus energy. The data points can be fit to a smooth curve for each source depth distribution.

  As noted before, a longer crystal would tend to yield a higher count rate in the field, meaning that the value of N_f/N_o would be > 1. For the source distributions generally encoun-tered, more than 80% of the uncollided flux is incident between $\theta = 30°$-$90°$ (θ measured from the detector axis normal to the ground interface). Uniformity of the zenith angular response in this range to within a few percent assures that the value of N_f/N_o will not vary significantly with changes in the distribution of flux. In general, a more uniform response is achieved with a crystal where the diameter is close to the length dimen-sion. However, the variation in N_f/N_o for a detector where the crystal length/diameter is as high as 1.3 or as low as 0.7 would not be expected to be more than about 20% for energies >200

keV. Figure 3.7 shows angular correction factor data at three different energies for several detectors in a downward facing geometry and a uniform source depth profile.

C. ϕ/I and ϕ/A.

The ϕ/I (and ϕ/A) factors are derived from γ-ray transport calculations. Tabulations of these data along with other pertinent information on the make-up of the environmental radiation field can be found in Beck et al. (1972), Beck and de Planque (1968), and Beck (1972). A complete set of exposure rate values (I/A) for close to 200 common fission and activation isotopes at various exponential depth distributions in the soil can be found in Beck (1980).

Notes:

1. The inference of exposure rates from nuclides located in the ground does not require a precise knowledge of the distribution with depth or of the exact soil density or composi-tion. This property results because the observed peak count rate in a field spectrum is essentially a measure of the uncollided flux, and although this quantity and the exposure rate produced by it and the associated scattered flux varies significantly with the source depth distribution and soil characteristics, the ratio of these two quantities, ϕ/I, does not. Thus, even a crude estimate of source distribution should not lead to a sizeable error in the exposure rate.

2. In lieu of a complete experimental calibration of a Ge detector for field spectrometry, generic factors may be substituted at energies > 200 keV (Helfer and Miller, 1988). The only parameters needed to apply this semiempirical calibration method are the manufac-turer's quoted efficiency at 1332 keV (5-45%), the crystal length/diameter ratio (0.5-1.3), and the detector orientation in the field (upward or downward facing). The accuracy of the derived factors is estimated to be ±10% for energies > 500 keV and ±15% for energies between 200 and 500 keV.

3.3.5 **SPECTRUM ANALYSIS**

In many situations, the built-in peak area estimate features of state-of-the-art analyzers are used in providing quick results in the field. Prominent peaks are identified in a bench-mark spectrum and the appropriate regions of interest are set up. On certain analyz-

ers, function keys are programmed using the net peak area, counting time and calibration factor (N_f/I and N_f/A) to provide instantaneous readout of exposure rate and concentration or inventory.

For more complete data reduction, a small computer is interfaced to the analyzer to run a spectrum analysis program. If desired, a totally portable system may be configured using a battery-powered laptop computer. Our standard analysis program (Gogolak and Miller, 1977; Gogolak, 1982) performs the following:

1. Based on a two point energy calibration as set by the operator, certain peaks which are characteristic of typical environmental spectra are identified, namely:

    a. the 186, 295, 352, 609, 1120 and 1765 keV peaks in the ^{238}U series;
    b. the 583, 911, 966 and 2615 keV peaks in the ^{232}Th series;
    c. the 1460 keV peak of ^{40}K;
    d. the 662 keV peak of ^{137}Cs.

    These peaks are defined by set energy bands where the left and right channel markers are representative of the Compton continuum.

2. The counts between the energy boundaries for each of the above peaks are summed. The background counts in three channels on each side of a peak are averaged and the result is used as an estimate of the baseline under the peak. This is multiplied by the number of channels in the peak and subtracted out from the total counts in the peak band to yield the net peak counts.

3. Detector specific calibration factors are applied to convert from peak count rate to exposure rate and concentration or inventory.

4. A printout is made listing count rates, converted quantities and associated statistical counting errors.

5. Permanent storage of the spectrum is made on either magnetic tape or diskette.

6. As an option, an automated search is performed to identify any peaks present in the spectrum. Data such as nuclide, half-life, γ-ray intensity and associated energy are printed out using a library of nearly 400 principal γ-ray energies that are seen in the environment (Section 5, this Manual). Any peak can be quickly analyzed by using an optional automated continuum strip.

7. The program enters an interactive phase where the operator examines any

additional peaks, checks the results of the automated routine, or investigates any unusual or unexpected features of a spectrum.

3.3.6 **INVENTORY MEASUREMENTS**

APPLICATION

A field γ-ray spectrum can also provide an estimate of the amount of activity per unit area of soil surface for nuclides which have been deposited on the ground. To do this, a knowledge of the source distribution in the soil is required in order to relate the measured total absorption peak count rate to the incident unscattered photon flux and then to the activity in the soil in a manner analogous to that used for natural emitters.

The activity profile with depth for deposited nuclides in undisturbed soils can be represented by an exponential function,

$$S \ = \ S_0 e^{-(\alpha/\rho)\rho z} \tag{4}$$

where

S   is   the activity per cm^3 at depth z cm,
S_o is   the activity per cm^3 at the soil surface,
α is   the reciprocal of the relaxation length in cm^{-1}, and
ρ is   the *in situ* soil density (g cm^{-2}).

The cumulative activity, or inventory I, integrated to depth z' is, then,

$$I \ = \ \int_o^{z'} dz \ = \ \frac{S_o}{\alpha}[1 - e^{-(\alpha/\rho)\rho z'}] \ = \ I_o[1 - e^{(\alpha/\rho)\rho z'}] \tag{5}$$

where I_o is the total inventory integrated to infinite depth.

HOMOGENEOUS TERRAIN

In the case of a freshly deposited nuclide, the depth parameter is infinite corresponding to a plane source distribution and a relaxation length of zero. In practice, the effects of ground roughness bury the source somewhat. Even on what appears to be flat terrain, we apply an α/ρ value of 6.25 cm^2 g^{-1}, which at a typical soil density of 1.6 g cm^3 corresponds to a relaxation depth of 0.1 cm. Values of α/ρ for aged global fallout ^{137}Cs have been found to range from a high of 1.0 for an evergreen forest floor to a low of 0.03 for a flood irrigated lawn. At a soil density of 1.6 g cm^3, these correspond to relaxation lengths of 0.6 and 21 cm, respectively. More typical values of α/ρ tend to range from 0.05-0.1 for open field sites and 0.2-0.5 for wooded or desert areas.

Values of the unscattered flux and its angular distribution at 1 m above the ground have been tabulated for exponentially distributed sources in the soil for various energies and α/ρ values (Beck et al., 1972). Using Equation 2, where the term A now represents the inventory (activity per unit area), the detector response can be calculated for a particular nuclide as a function of α/ρ. If the nuclide has two reasonably strong γ lines well separated in energy, the value of α/ρ can be inferred from the ratio of the measured fluxes.

In the case of a monoenergetic source such as ^{137}Cs, the value of α/ρ can be determined experimentally as follows:

1. A 62 cm^2 or similar large area corer and auger is used to extract soil samples from different depth intervals (see Section 2.4) depending upon the expected activity distribution. For example, if the profile is expected to be shallow, the depth intervals can be 0-2.5, 2.5-5, and 5-30 cm, while if it is expected to be deep, intervals of 0-5 cm, 5-10 cm, and 10-30 cm can be used. More than one core can be taken, in which case the samples from the same depth are composited. The depth of the soil core should be sufficient to include essentially all of the deposited activity so that I can be determined.

2. An aliquot of a sample from each depth increment is counted on a high resolution Ge detector to determine the concentration of the radionuclide of interest.

3. The activity per unit area for each depth is computed from the product of the concentration and the sample mass for that depth increment divided by the area of the sample.

4. A fit to Equation 5 is then applied, the variables being $I - I$, the integrated activity per unit area and $\rho z'$, the gross *in situ* mass per unit area down to depth z. Graphically, this